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The sources and prevalence of anthropogenic noise in Rockfish Conservation Areas with implications for marine reserve planning

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ABSTRACT

Underwater noise pollution is a recognized threat to marine life. In British Columbia, Canada, Pacific rockfish (*Sebastes* spp.) were historically overfished, prompting the establishment of Rockfish Conservation Areas (RCAs). However, there are no restrictions prohibiting vessel transits in RCAs. We hypothesized that RCAs do not protect rockfish from sub-lethal harm from noise. We compared noise levels at three RCAs with adjacent unprotected reference sites from August 2018–June 2019. While RCAs had lower levels of noise overall than reference sites, this trend was inconsistent; some RCA sites had higher levels of noise during certain time periods than non-RCA sites. A vessel noise detector was the best predictor of noise level over three frequency bands (20–100 Hz, 100–1000 Hz, 1–10 kHz), and predicted sound levels which could mask rockfish communication. We conclude that RCAs do not reliably protect rockfish from noise pollution, and recommend further study into potential impacts on stock recovery.

1. Introduction

Underwater noise pollution is now a globally-recognized conservation concern for aquatic animals (Erbe et al., 2012; Frisk, 2012; Cox et al., 2018; Kuşku et al., 2018; Pirotta et al., 2019). Noise-generating human activities in marine environments such as commercial shipping, recreational boating, pile-driving, seismic exploration, and offshore energy production are widespread and increasing (Hildebrand, 2009), and noise from these activities, even if undertaken outside of marine protected areas, propagates into marine protected areas (Buscaino et al., 2016). Noise pollution with high source levels can propagate hundreds of kilometers under the right conditions (Richardson et al., 2013). Expansion of marine-based industries such as oil and gas exploration and extraction, intercontinental shipping, and marine tourism will continue to increase levels of anthropogenic noise in coastal oceans (Frisk, 2012). If this economic expansion is to be ecologically sustainable, it is imperative that we better understand how current and rising noise levels will impact ecosystems. To date, there has been considerable study worldwide on the impacts of anthropogenic noise on marine mammals (*e.g.* Tyack, 2009; Erbe et al., 2016), resulting in policy governing noise levels within critical habitat (NOAA, 2019). However, the impact of noise on marine fish, which make up a large percentage of biomass in the ocean and are important as food sources both for marine animals and humans (FAO, 2012), is vastly under-represented in the scientific literature and in policy (Popper and Hastings, 2009; Ladich, 2013; Popper et al., 2020). There is much to be understood about how noise affects fish and how an increase in anthropogenic underwater noise may impact fish stocks and ecosystem health, including inhibiting the recovery of depleted fisheries.

Existing research has found that anthropogenic noise can lead to physical damage, physiological stress, and behavioural changes in fish (Popper and Hastings, 2009; Kuşku, 2020; Kuşku et al., 2020). Continuous noise, such as that from vessel traffic, can lead to behavioural effects that may have chronic impacts on fish health (Slabbekoorn et al., 2010; Radford et al., 2014; Cox et al., 2018). Fish responses to anthropogenic noise may include spatial avoidance of noise, adjustments of the sounds emitted by fish such as increased amplitude (*i.e.* the Lombard effect), frequency shifts of vocalizations, and changes in signalling

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modality (Radford et al., 2014; Luczkovich et al., 2016). Vessel noise also decreases the ability of fish to detect acoustic signals, reducing the range within which conspecific communication may be possible (Vasconcelos et al., 2007; Ladich, 2013; Stanley et al., 2017) and masking signals from predators, increasing fish mortality by predation (Simpson et al., 2016).

In British Columbia (BC), Canada, several species of rockfish (Family Sebastidae; *Sebastes* spp.) are important to commercial, recreational, and Indigenous fisheries (Yamanaka and Logan, 2010; Tonnes, 2011; Eckert et al., 2018); however, many species of rockfish are currently experiencing stock declines due to historical overharvesting and undermanagement (O'Farrell and Botsford, 2006). Rockfish are long-lived, slow to mature and undergo an exponential increase in fecundity with age (Love et al., 1990; Dick et al., 2017); they are therefore slow to recover from stock depletion. Several species of Pacific rockfish produce low-frequency, low-amplitude vocalizations which are thought to function in agonistic and spawning behaviours (Nichols, 2005; Širović and Demer, 2009). While not all species of Pacific rockfish have known vocalizations, many of them possess similar sound-production and reception organs and it is likely that most members of this genus have similar auditory capabilities. To our knowledge, there are currently no published audiograms for any Pacific rockfish species, although it can be assumed that they perceive sound within the frequency range of their vocalizations. However, few rockfish vocalizations recorded in the wild have been attributed to a particular species (Nichols, 2005; Širović et al., 2009). Therefore, inferring rockfish perception of sound through vocalization frequency can only be applied at the genus level. While there are data to suggest that high amplitude, impulsive sounds from seismic air guns produce a startle response in captive rockfish (Pearson et al., 1992) and appear to displace rockfish in the wild (Skalski et al., 1992), there has been no research on the effect of lower-amplitude, continuous noise from vessels on rockfish populations.

The current recovery plan for rockfish in BC includes Rockfish Conservation Areas (RCAs): habitat defined by chart coordinates in which catch or by-catch of rockfish is prohibited (Yamanaka and Logan, 2010). On Canada's Pacific coast, the dominant source of anthropogenic noise is that produced by vessel activity from shipping, recreation, tourism, and fishing (Erbe et al., 2012; Houghton et al., 2015). Vessel noise is classified as a continuous noise source, and the close passage or combined noise of several ships can create substantial increases in sound intensity (Bassett et al., 2012; Erbe et al., 2012). In the inland waters between lower Vancouver Island and the mainland of BC and Washington State, many RCAs coincide spatially with busy shipping lanes, ferry routes, ecotourism destinations, harbours, and marinas (Fisheries and Oceans Canada, 2008; Yamanaka and Logan, 2010). The noise produced by motorized vessels overlaps in frequency band with the sounds produced by rockfish (Širović and Demer, 2009). Currently, no restrictions are placed upon vessels transiting or conducting other operations inside or near RCAs.

There are currently no published data on the level of anthropogenic noise experienced by rockfish in RCAs. We used passive acoustic monitoring to characterize the level and temporal patterns of anthropogenic noise experienced in three RCAs, and compared them to adjacent non-protected areas with similar bathymetry and habitat quality to assess whether RCAs offer refuge from noise pollution. To quantify vessel presence, we used Automated Identification System (AIS) data to determine the number of AIS-enabled ships passing each recording station. We also used a vessel detector to identify recordings containing vessel noise. Using these sources as well as environmental data (wind speed and direction), we attempted to explain differences in sound pressure levels at three frequency bands (20–100 Hz, 100–1000 Hz, and 1–10 kHz). We also examined vessel presence and environmental factors to explain noise levels that would likely cause communication masking in rockfish, which may cause behavioural disturbance. Understanding the current sources and patterns of noise in RCAs will help managers to further evaluate the effectiveness of this conservation method, as well as informing the planning and implementation of future marine reserves.

2. Materials and methods

2.1. Site description

The Salish Sea comprises the waterways of the Strait of Juan de Fuca, Haro Strait, and Puget Sound. These waterways encompass the marine portion of the international border between the province of BC in Canada and Washington State in the United States of America, which connects the coastal cities of Vancouver, Victoria, and Seattle. The present study took place in the Canadian portion of the Salish Sea, in northern Juan de Fuca and western Haro Straits, adjacent to the towns of Victoria and Sidney, BC (Fig. 1).

Three RCAs were selected for monitoring based on their proximity to various sources of vessel traffic and the presence of suitable benthic composition of approximately equal depth among sites (determined using charts produced by the Canadian Hydrographic Service; www.charts.gc.ca). The northernmost RCA site was Fernie Island, inside the Coal Island RCA, located close to the town of Sidney and its associated marina and yacht club, as well as the nearby Swartz Bay ferry terminal (≤50 departures and arrivals/day). The westernmost site was Duntze Head RCA, located between Victoria Harbour (an international harbour serving passenger ferries, ecotourism vessels, a commercial fishing fleet, a pilot station, a seasonal cruise ship port, and other activities) and Canadian Forces Base Esquimalt. The third RCA site was Discovery/Chatham Island RCA, located adjacent to a thoroughfare for seasonal eco-tours and recreational boat traffic, as well as the international shipping lane in Haro Strait. Each RCA site was paired with an unprotected reference site nearby (Armstrong Point, Macaulay Point, and Spring Bay, respectively) with similar-quality rockfish habitat and similar orientation with respect to vessel traffic sources (Fig. 1). Wherever possible, paired recording units were deployed at similar depth and with similar distance to rocky habitat. However, some trade-offs were made in order to ensure the security of recording devices and the quality of acoustic data collected. For example, the Discovery/Chatham Island RCA is much closer to the busy shipping lane than its paired site at Spring Bay, whereas Fernie Island, inside the Coal Island RCA, is not as close to a ferry terminal and boat launch as its paired reference site at Armstrong Point (Fig. 1, Table 1).

2.2. Hydrophone deployments

Recorders were deployed over three time periods from late summer 2018 to early summer 2019, with each deployment lasting between six and eight weeks. The recording periods were August 21st–October 9th, 2018 (49 days), January 28th–March 15th, 2019 (46 days), and May 3rd–June 29th, 2019 (57 days). During each period, a SoundTrap ST300 acoustic recorder (Ocean Instruments, New Zealand) was deployed at each of the six sites at depths of 6.7–13.1 m (Table 1). All units recorded on a 1:6 duty cycle: 5 min of recording every half hour, in the bandwidth from 20 Hz to 24 kHz (sampling rate of 48 kHz, high gain setting). Acoustic recorders were housed in open PVC tubes for protection, with windows cut around the hydrophone itself to allow acoustic permeability. The tubes were secured horizontally to ~11.5 kg weights and placed by SCUBA divers on an area of the bottom with a flat profile and soft sediment substrate, within approximately 10 m of primary rockfish habitat (*i.e.* rocky substrate with macroalgal coverage). This placement ensured that the received levels would be similar to what rockfish in the immediate area would be exposed to, without interference or incidental noise from surrounding rocks or blades of macroalgae moving in the current. Deployment depths varied slightly due to minor differences in topography between sites (Table 1). Care was taken to place the units at the same coordinates (within 5 m) each time they were deployed. Units were left to passively record and were retrieved by divers several weeks later. Analysis was restricted to include the same time period among all

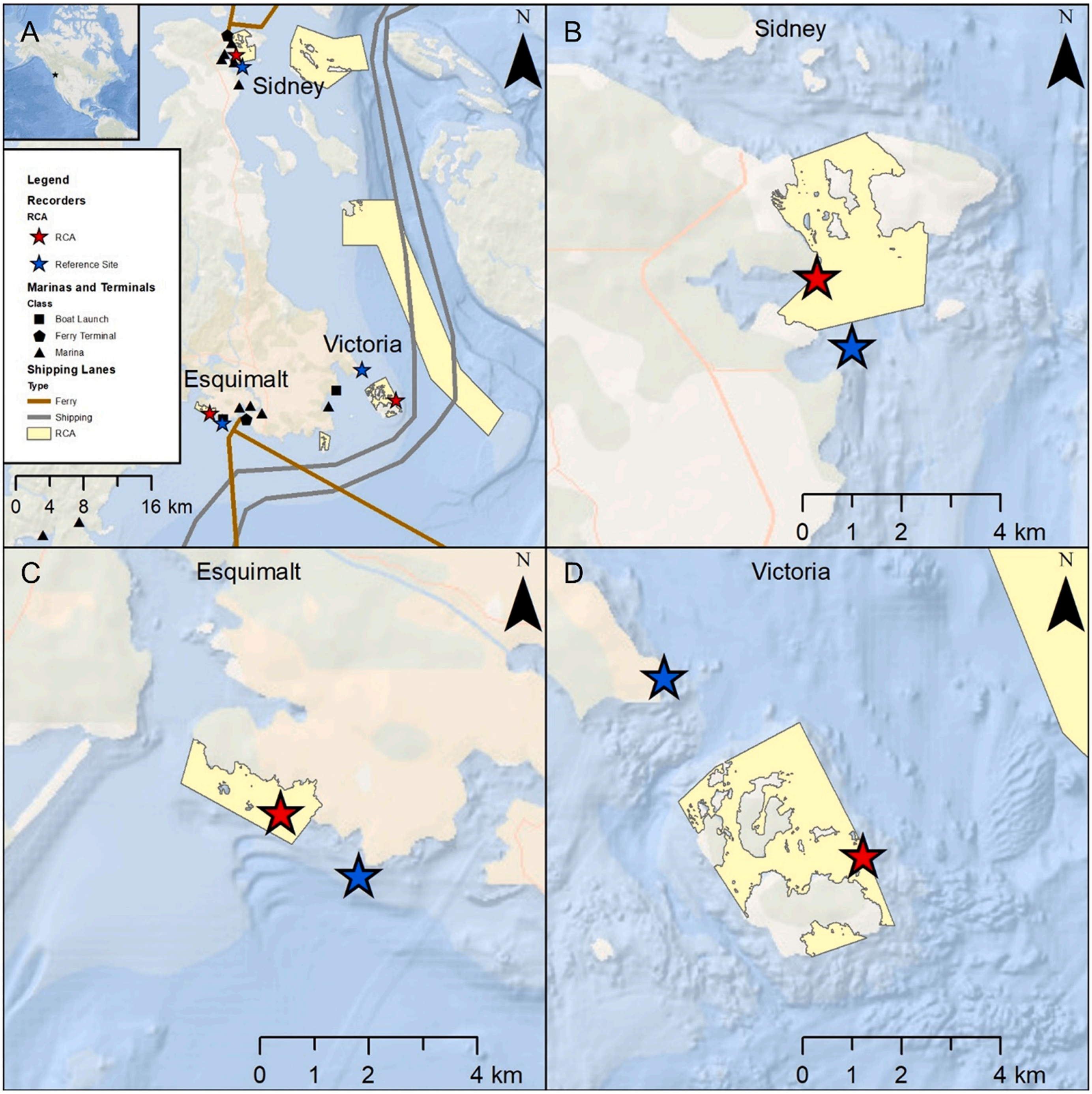

Fig. 1. Map showing selected RCAs and reference sites in the southern Salish Sea, with sources of vessel noise and ferry/shipping routes (~10–20 passages/day) identified (A). Stars indicate our six recording sites: three RCA sites (red) and three adjacent unprotected reference sites (blue). Paired sites for comparison are in the regions of Sidney, Victoria, and Esquimalt. B–D are higher resolution views of the recording sites for each paired site. All RCA sites were completely within the RCA boundaries. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sites for each deployment period.

2.3. Rockfish surveys

During all deployments and retrievals, divers performed rapid visual count (RVC) surveys of the rockfish communities at each site following (Kimmel, 1985; Karnauskas et al., 2011) to assess presence/absence and verify that these locations were indeed inhabited by rockfish. Two five-minute RVCs were conducted at each site by two divers swimming in tandem, with 50–75 m examined during each. Replicate surveys paths did not overlap, allowing for rockfish counts at each site to be summed to create a single datum. Annual surveys of rockfish for monitoring purposes suggest that several rockfish species behave more cryptically with respect to visual surveys over the winter and spring months (Borden et al., 2018); however, we were not originally interested in seasonal abundance, only in presence/absence, and did not take this pattern into account in our survey design. In addition, some of our surveys were conducted during the peak visibility time for visual SCUBA surveys, from August to October (Borden et al., 2018), and therefore we assumed that relative numbers during each surveying period were representative

Table 1
Deployment information for six SoundTrap ST300 recording units at three RCA sites (Duntze Head, Discovery Island, and Fernie Island) and three adjacent unprotected reference sites (Macaulay Point, Spring Bay, and Armstrong Point). Region refers to the three pairs of sites (see Fig. 1). Depths were recorded by divers at the time of deployment and were subject to tidal changes. Coordinates and depths varied slightly (~5 m) among the three deployments; therefore, a range of depths is given, and coordinates are truncated to 3 decimal places for each site. RCA sites are shaded grey; unprotected sites are unshaded.

Region	Site ID	Depth (m)	Latitude (°N)	Longitude (°W)
Esquimalt	Duntze Head	7.3-11.0	48.422	-123.425
	Macaulay Pt.	11.6-13.1	48.415	-123.412
Victoria	Discovery I.	7.6-10.4	48.433	-123.226
	Spring Bay	10.1-12.2	48.453	-123.264
Sidney	Fernie I.	6.7-7.6	48.674	-123.397
	Armstrong Pt.	11.3-13.1	48.665	-123.391

of differences among sites.

2.4. Acoustic analysis

All acoustic recordings for each site were batch processed for each of the three deployment periods using the PAMGuide package (Merchant et al., 2015) in MATLAB (version 2019a; Mathworks Inc.). Calibrated broadband sound pressure levels (SPL; dB re 1 μPa) were produced in 60 s intervals for the bandwidths 20–100 Hz (hydrophone sensitivity declines below 20 Hz for these acoustic recorders), 100–1000 Hz, and 1–10 kHz. The lowest-frequency bandwidth should contain low-frequency noise from shipping vessels, environmental noise from tidal sources, as well as some rockfish vocalizations (Nichols, 2005; Merchant et al., 2014); the middle-frequency analysis band should contain rockfish vocalizations and higher-frequency vessel noise; and the highest-frequency analysis band should contain the high-frequency noise from vessels that are closer to the recorder (Veirs et al., 2016), sediment entrainment, and some marine mammal vocalizations (Merchant et al., 2014). Wind-driven environmental noise should be present in all bandwidths (Wenz, 1962).

No thresholds for the potential onset of behavioural effects for fishes are yet known; however, the source levels of captive rockfish vocalizations were recorded as 103–113 dB re 1 μPa at 1 m (Širović and Demer, 2009). To estimate a disturbance threshold for rockfish, we averaged the SPL over the critical bandwidths at which rockfish vocalize (20 Hz–1 kHz; Širović and Demer, 2009) for each 5 min recording. Since rockfish vocalize in this frequency range, it can be assumed that their peak auditory sensitivity is in a similar bandwidth, and that noise in this bandwidth exceeding the highest recorded source level for rockfish (113 dB re 1 μPa at 1 m; Širović and Demer, 2009) could incur behavioural disturbance *via* communication masking (Clark et al., 2009). The average SPL in the 20 Hz–1 kHz bandwidth was then compared to a threshold of 113 dB re 1 μPa. Recordings in which the averaged SPL in the 20 Hz–1 kHz bandwidth for rockfish exceeded 113 dB re 1 μPa were given a value of 1, and those recordings in which the threshold was not reached were given a 0, for a binomial response.

2.5. Vessel noise

Boat noise and the amount of shipping activity were estimated in two ways. The first was based on satellite Automatic Identification System data (exactEarth, Cambridge, ON, Canada), where we counted the number of AIS-enabled vessels that transited within a radius of 1 km, 5 km, and 10 km of the acoustic recorder within each hour of recording to qualitatively explain broader spatial/temporal trends in the SPL data. Additionally, the number of AIS-enabled vessels at each range during the 5 min recording periods was recorded for direct comparison with SPL observations. However, AIS-enabled vessels do not represent the entire suite of vessels that may be audible from each of the six listening stations. Recreational vessels may be more important sources of noise at certain sites, and most of these do not carry AIS transponders (Hermannsen et al., 2019).

In order to include recreational vessels as well as AIS-enabled vessels in our analysis, we produced a vessel presence/absence metric using a vessel-noise detection algorithm in MATLAB. The detector is first triggered by sound pressure levels, averaged every 2 s, exceeding a dynamic threshold (set at 5 dB above the 10th percentile of the recording) for at least 10 s and monitors the levels until it drops below the threshold value for another 2 s (if the end of the recording is reached beforehand, the end of the trigger duration is the end of the recording). If the end of the file is reached before the initial 10 s is reached, the file is set aside in a separate directory, along with its spectrogram, for manual verification. Upon a successful trigger, the corresponding data were then extracted and the DEMON (Detection of Envelope Modulation on Noise) spectrum was processed, as well as the raw spectrogram analyzed for any Llyod mirror patterns from fast-moving power boats. The presence of spikes in the DEMON power spectrum indicated tonals associated with vessels, and the detection was made if the spikes exceed twice the standard deviation of the average levels across all frequencies. Finally, the DEMON spectrogram was binarized and moved to a separate directory for manual verification, along with the DEMON power spectrum, raw spectrogram and a .WAV file of the detection. All detections were verified by examining these. All files were processed for vessel detections, and were assigned a binary response: either vessels were detected in the 5 min recording period, or they were not.

2.6. Statistical analysis

To determine the extent of the difference in mean sound pressure between RCA and unprotected reference sites at the three target bandwidths, as well as among recording periods (season: Fall, Winter, or Spring), we fitted linear mixed-effect models for each bandwidth using the ‘lme4’ package (Bates et al., 2015) in R (version 3.4.3; R Core Team, 2017), with protection status and season as fixed effects. As we were also interested in the extent of the variance among sites but not in the estimated differences themselves, the region of the paired sites (Victoria, Esquimalt, or Sidney) was added to each model as a random effect. Results for fixed effects are reported as estimated effect size ± standard error.

To investigate possible explanatory factors in the mean broadband sound pressure levels at each of the three target bandwidths, we analyzed hourly environmental data from Environment and Climate Change Canada (wind speed and direction; http://climate.weather.gc.ca/historical_data). Because the environmental data were collected on the hour, the acoustic data were divided and only the recordings from the top of each hour were used for comparison to ensure similar temporal resolution. We included wind speed and direction in this analysis because wind is one of the dominant drivers of underwater sounds levels in the ocean (Wenz, 1962). We did not include tide height in our analysis because a preliminary analysis demonstrated that tide height was not an important predictor of SPL (K. Nikolich, unpublished data). To rule out redundant variables and avoid over-fitting, we used logistic regression to determine whether AIS vessel counts were strongly autocorrelated to the presence or absence of automated vessel detections in each file. Three models were fit with detection (binary) as the outcome and AIS vessel count (one model for each radius, see below) as the explanatory factor. Since *p*-values were likely to be low due to large sample sizes, models were evaluated using R^2 values. Logistic regressions were performed using the basic package in R (version 3.4.3; R Core Team, 2017).

To assess the importance of natural and anthropogenic sound sources contributing to the SPL at the three target bandwidths, we fitted a generalized linear mixed-effects model in R (Bates et al., 2015; R Core Team, 2017) with SPL in each bandwidth as the dependent variable. To determine which AIS radius (1, 5, or 10 km) to include in the model for each bandwidth, the Akaike Information Criterion (AIC) scores were compared among full models (Bolker et al., 2009); the full model with the lowest AIC score represented the radius that best explained SPL at that bandwidth. The full model also included vessel detections using the automated algorithm (binary value), wind speed (kts), wind direction (N/E/S/W), and region (Pair: Esquimalt, Victoria, or Sidney), as well as all acoustically-relevant two-way interactions as fixed effects. Site (one of six individual recording locations) was included as a random effect. The full and null models were fitted for each bandwidth, as well as models excluding certain fixed factors and their corresponding interactions to determine the most important predictive variables. The model with the lowest AIC value for each bandwidth was determined to be the best explanatory model for sound pressure level within that bandwidth, and the factors that incurred the largest rise in AIC value when excluded from the full model were considered to be the most important predictors of SPL in that bandwidth.

Finally, we applied the data to examine the possibility of biological disturbance in rockfish. We used a generalized linear model with a binomial distribution to determine whether any of the factors examined above (*i.e.* vessel detections, AIS, wind speed, wind direction, region, and two-way interactions among the latter three) significantly predicted whether the averaged SPL in the critical bandwidth for rockfish vocalizations exceeded our theoretical disturbance threshold of 113 dB re 1 μPa.

3. Results

Acoustic recordings were taken for 5 min every half hour for the entirety of each deployment period. The recording periods for analysis were referred to as Fall (49 days/2340 recordings per site; n = 14,040), Winter (46 days/2190 recordings per site; n = 13,140), and Spring (57 days/2720 recordings per site; n = 16,320). The total sample size across all six sites and three deployments was N = 43,494 successful recordings. Due to mechanical error, a total of six sound files across four sites were not successfully recorded, and were disregarded. Because the sample sizes were so large, statistical significance while modelling was common, and should be considered in conjunction with effect size to better assess actual biological significance.

3.1. Rockfish surveys

A total of 424 rockfish were observed by divers during a total of 6 h of surveying. Counts were highly variable among sites and among seasons, with most rockfish observed in late August, and fewest observed in early May. The sites that had the highest number of rockfish were Discovery Island (RCA; Victoria), where rockfish counts were consistently among the highest of all sites, and Armstrong Point (unprotected; Sidney), which had very high rockfish counts in the late summer/fall (August and October surveys), but very few rockfish seen in the winter and spring/early summer. When summing each site's six surveys, overall the RCAs in Esquimalt and Victoria had more rockfish than the unprotected sites; however, the unprotected site in Sidney had more rockfish overall than its paired RCA site (Table 2).

3.2. Acoustic analysis

Three linear mixed-effect models were produced: one for each target bandwidth as the response, with the fixed factors of protection status (RCA *vs.* unprotected) and season (Fall, Winter, or Spring), and the random factor of region (Pair: Esquimalt, Victoria, or Sidney). For the bandwidth of 20–100 Hz, the RCA sites had a higher noise level than the unprotected sites, but the effect size estimate (shown as estimate ± standard error) was minimal (−1.04 ± 0.06 dB re 1 μPa, $t_{4349} = -18.3$, $p < 0.001$). There was no significant difference between spring and either previous season ($t_{4349} = -1.3$, $p = 0.180$; Fig. 2). There was a significant difference between fall and winter at this bandwidth ($t_{4349} = -10.8$, $p < 0.001$; Fig. 2); however, the difference was small (−0.78 ± 0.07 dB re 1 μPa; Fig. 2). The mean difference ± standard deviation among pairs was 3.2 ± 1.8 dB re 1 μPa, which appears to be influenced strongly by the wider variance in Victoria sites (Fig. 3). Overall, the lowest bandwidth was fairly homogenous across time, region, and protection status.

For the bandwidth from 100 to 1000 Hz, the RCA sites were less noisy than the unprotected sites by 5.02 ± 0.09 dB re 1 μPa ($t_{4349} = 57.21$, $p < 0.001$). Winter had 2.15 ± 0.11 dB re 1 μPa lower SPL than fall ($t_{4349} = -19.34$, $p < 0.001$; Fig. 2), which was another 2.45 ± 0.11 dB re 1 μPa lower than spring ($t_{4349} = 23.30$, $p < 0.001$; Fig. 2). The mean difference among regions was greater in this bandwidth, estimated at 19.51 ± 4.42 dB re 1 μPa (Fig. 3). Overall, this middle bandwidth showed greater differences among seasons and among regions than the lowest bandwidth.

In the bandwidth from 1 to 10 kHz, RCA sites again had lower SPL values than unprotected sites ($t_{4349} = 76.5$, $p < 0.001$), by an estimated 6.56 ± 0.09 dB re 1μPa. Fall had the lowest SPL values and spring the highest ($t_{4349} = 36.45$, $p < 0.001$; Fig. 2), with a total estimated difference of 3.75 ± 0.10 dB re 1 μPa. The noise level in winter fell between the other seasons, approximately 1.91 ± 0.11 dB re 1 μPa higher than fall ($t_{4349} = 17.61$, $p < 0.001$; Fig. 2). The mean difference among regions in this bandwidth was not as high as for the middle bandwidth but was still notable with a variance of 6.65 ± 2.58 dB re 1 μPa (Fig. 3).

When examining the average SPL in the critical bandwidth for rockfish vocalizations, we found that every site experienced an SPL over 113 dB re 1 μPa (our threshold for behavioural disturbance) at some point during each the recording periods. Two reference sites (Macaulay Point and Armstrong Point) had a total of 27.0% and 23.8% of all

Table 2
Rockfish (*Sebastes* spp.) counts at each of the six study sites, as recorded by scientific divers concurrently while deploying (August, January, May) or retrieving (October, March, June) acoustic recording equipment. Two 5 minute rockfish surveys were complete at each site during each deployment or retrieval event, and the counts were added for a total out of 10 min of surveying. The RCA sites are shaded grey; unprotected sites are unshaded. Paired regions were Esquimalt (Duntze Head & Macaulay Point), Victoria (Discovery Island & Spring Bay), and Sidney (Fernie Island & Armstrong Point).

	Survey Month						
Site ID	August	October	January	March	May	June	**Total**
Duntze Head	1	0	0	0	0	75	**76**
Macaulay Pt.	1	1	0	0	0	0	**2**
Discovery I.	79	67	16	6	2	7	**177**
Spring Bay	1	1	1	0	0	0	**3**
Fernie I.	0	0	0	2	0	10	**12**
Armstrong Pt.	105	46	1	0	2	0	**154**
Total	**187**	**115**	**18**	**8**	**4**	**92**	

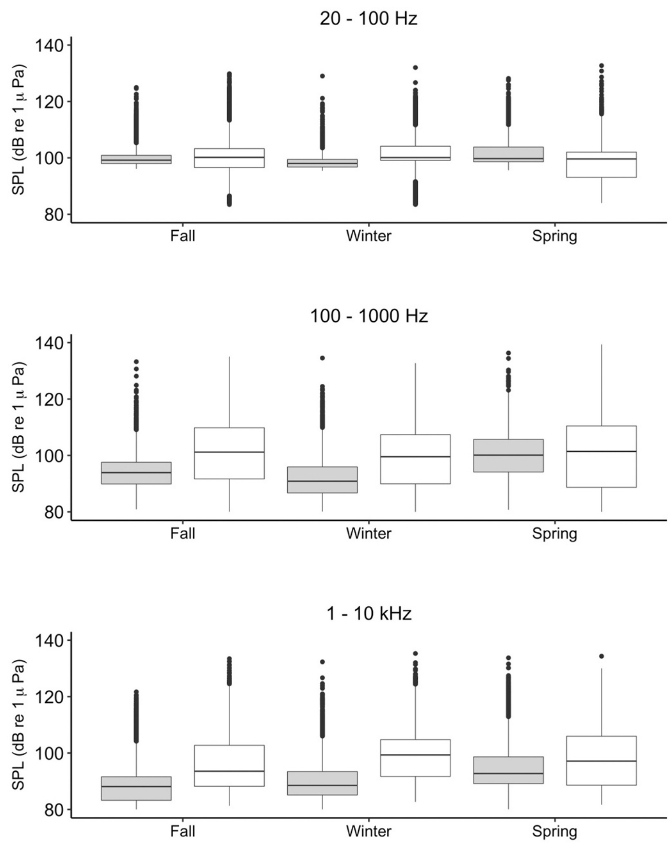

Fig. 2. Summary of variation in sound pressure level (SPL) for three target bandwidths, grouped by recording period (see Materials and methods for dates). Grey boxes indicate the RCA site for each region; white boxes indicate the paired reference site.

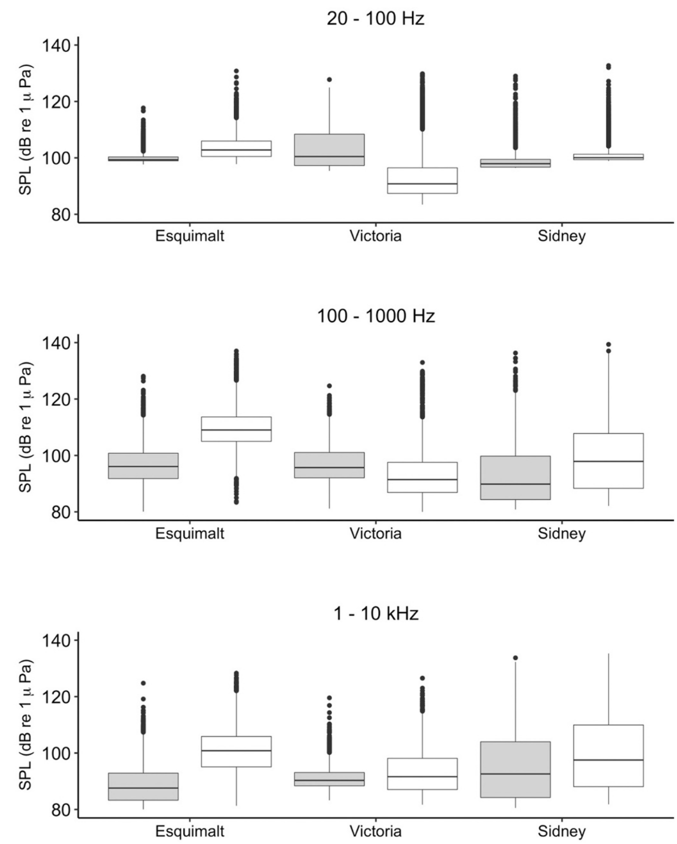

Fig. 3. Summary of variation in sound pressure level (SPL) for three target bandwidths, grouped by region (see Table 1 for coordinates). Grey boxes indicate the RCA site for each region; white boxes indicate the paired reference site.

recordings over this limit, respectively, over all three seasons (Fig. 4). Two RCA sites (Discovery Island and Fernie Island) had SPLs exceeding the disturbance limit in 10.2% and 4.8% of recordings overall, respectively, with the most exceedances occurring in the spring (Fig. 4).

3.3. Vessel presence

A summary of the total hourly AIS vessel counts showed that the Sidney pair (Fernie Island and nearby Armstrong Point) had the most vessel passages overall throughout the year at any radius. Furthermore, Fernie Island (inside Coal Island RCA) consistently had by far the most AIS-enabled vessel passages within a 1 km distance throughout the year. The Victoria pair (Discovery Island RCA and Spring Bay) consistently had the fewest vessels passing at the 10 km and 5 km range, and almost always the fewest at the 1 km range. The Esquimalt pair (Duntze Head RCA and Macaulay Point) consistently had more vessels than Victoria at 10 km and 5 km, but fewer than Sidney at the same distances. However, the Esquimalt pair had very similar vessel counts to Victoria at the 1 km range, apart from slightly lower counts during winter (Table 3).

Using the verified vessel noise detection algorithm, tonal signatures from vessels were detected in a total of 750 recordings (0.22%) at Duntze Head RCA, 1690 recordings (9.34%) at Macaulay Point, 990 recordings (1.20%) at Discovery Island RCA, 2169 recordings (2.12%) in Spring Bay, 3669 recordings (2.79%) at Fernie Island (Coal Island RCA), and 3879 recordings (10.91%) at Armstrong Point. The Esquimalt pair (Duntze Head and Macaulay Point) had the fewest detections overall, followed by the Victoria pair (Discovery Island and Spring Bay). This is in contrast to the AIS data, which found the Victoria pair to have fewer vessel passages than the Esquimalt pair (Table 3). The Sidney pair (Fernie Island and Armstrong Point) had the most vessel detections by

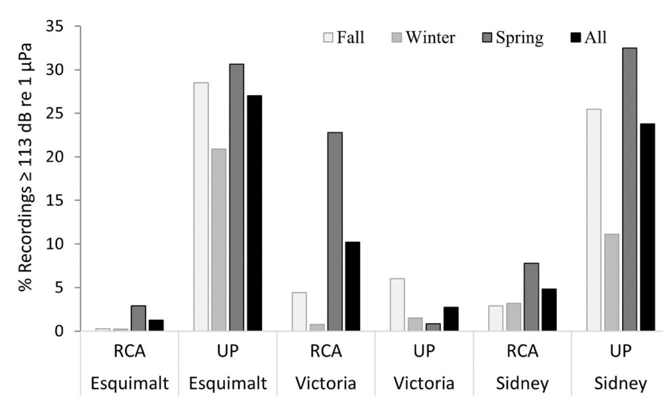

Fig. 4. The percentage of recordings at each site per recording period that had an average sound pressure level (SPL) greater than or equal to 113 dB re 1 μPa in the critical bandwidth for rockfish, which is a theoretical threshold for behavioural disturbance in rockfish. The top line of the x-axis label denotes the protection status of the site (RCA = Rockfish Conservation Area; UP = adjacent unprotected habitat), and the bottom line of the x-axis label denotes the region of the site (paired locations in the Salish Sea).

far, echoing the trend found using the AIS method.

3.4. Factors influencing SPL

Before modelling, we confirmed that the two ways of quantifying vessel traffic were not tightly autocorrelated. Logistic regression showed a significant correlation between vessel noise detections and AIS vessel

Table 3
Summary of the number of AIS vessels recorded within three nested radii of each recording site every hour, for all hours that recording units were deployed. RCA sites are shaded grey; unprotected sites are unshaded. Paired regions were Esquimalt (Duntze Head & Macaulay Point), Victoria (Discovery Island & Spring Bay), and Sidney (Fernie Island & Armstrong Point). Mean values are given ± standard deviation.

	Fall			Winter			Spring		
Site ID	10 km	5 km	1 km	10 km	5 km	1 km	10 km	5 km	1 km
Duntze Head	6.3±2.9	4.9±2.4	0.1±0.4	6.0±2.8	4.3±2.3	0.2±0.4	8.6±1.4	6.4±1.2	0.1±0.1
Macaulay Pt.	6.6±3.0	5.2±2.5	0.3±0.7	6.3±3.0	4.6±2.4	0.2±0.5	9.1±1.5	6.7±1.2	0.3±0.2
Discovery I.	3.0±2.1	1.8±1.5	0.1±0.3	2.6±2.0	0.1±0.9	0.04±0.2	3.8±0.9	2.0±0.5	0.1±0.04
Spring Bay	5.5±2.7	1.1±1.2	0.3±0.6	4.9±2.3	1.1±1.1	0.1±0.3	7.8±1.3	1.9±0.5	0.4±0.3
Fernie I.	8.8±3.0	7.3±2.3	2.1±1.0	11.3±2.6	10.4±2.3	3.7±1.0	9.6±1.5	8.2±1.0	2.6±0.2
Armstrong Pt.	8.8±3.0	7.3±2.3	0.2±0.5	11.4±2.6	10.3±2.3	1.0±0.8	9.8±1.5	8.2±1.0	1.1±0.2

counts for each range; however, this was likely due to the large sample size. All R^2 values were low (0.02–0.07) for these models, and data visualization showed a considerable influence of zero values in the AIS vessel count, especially at 1 km range (Fig. 5). Thus, both measurements of vessel traffic were included in the explanatory models. In each bandwidth, AIS vessel counts at 1, 5, and 10 km radii were compared using AIC values for each radius in the full model.

In each bandwidth, vessel counts at 1 km were least explanatory, and vessel counts at 10 km were most explanatory (Δ $AIC_{20–100\ Hz} = 11.9$, Δ $AIC_{100–1000\ Hz} = 79.9$, Δ $AIC_{1–10\ kHz} = 229.2$), with the 5 km radius falling in between. Thus, AIS vessel count at the 10 km radius was used as a factor in the full explanatory model for all bandwidths. When generalized linear mixed-effect models were fit to investigate the most important factors in determining broadband SPL from 20 to 100 Hz, 100–1000 Hz, and 1–10 kHz, the SPL in each bandwidth was best explained by the full model, containing the number of AIS vessels within a 10 km radius, presence/absence of automated detection, wind speed, wind direction, region (pair), two-way interaction terms, and the random factor of site (individual recorder locations; see Table 1). In each bandwidth, the least explanatory model was the null model, containing only the random factor of protection status.

At all bandwidths, the factor which incurred the largest rise in AIC value when removed was presence/absence of vessel detections, implying that noise from vessels was the most important explanatory factor at all bandwidths. At 20–100 Hz, the next most important factors according to model selection (in descending order) were wind direction, region (pair), two-way interaction terms, and wind speed; the least important factor at this bandwidth was AIS vessels within 10 km. At 100–1000 Hz, the next most important factors in descending order were wind direction, wind speed, two-way interaction, and region; the least important factor was AIS vessel count within 10 km. At 1–10 kHz, the next most important factors in descending order were two-way interactions, wind speed, wind direction, and AIS vessels within 10 km; the least important factor was region (Table 4).

In the 20–100 Hz bandwidth, the presence of vessel detections had a significant positive impact on SPL, with an effect size of 2.2 ± 0.08 dB re 1 μPa ($t_{21640} = 26.53$, $p < 0.001$). The number of AIS vessels at 10 km radius was also a significant factor ($t_{21640} = 3.96$, $p < 0.001$); however, the effect size was much smaller (0.07 ± 0.02 dB re 1 μPa). There was a significant interaction between wind speed and region: wind speed had a greater positive relationship with SPL at the Victoria sites than at other regions (0.053 ± 0.01 dB re 1 μPa/km/h, $t_{21640} = 4.74$, $p < 0.001$). There were also significant interactions between wind direction and region: westerly wind was more positively associated with SPL in

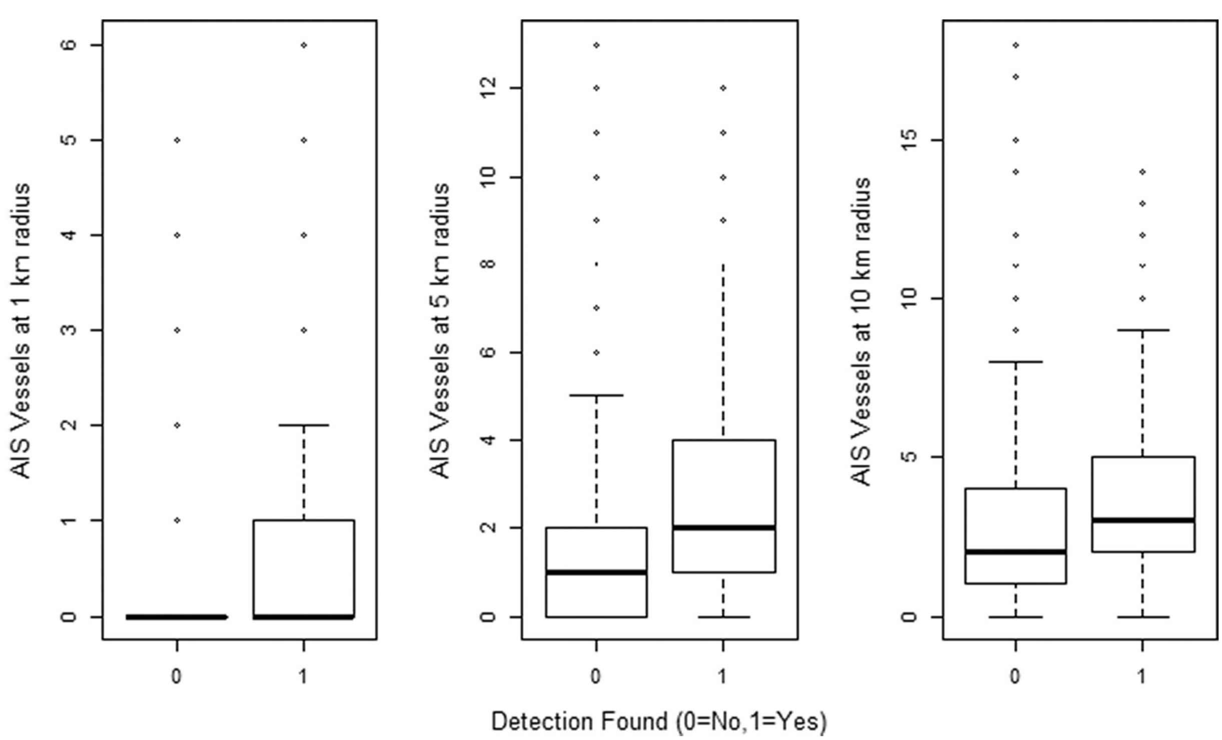

Fig. 5. The number of AIS-enabled vessels counted within each 5 min recording time at three ranges from the recorder (1 km, 5 km, and 10 km), compared to whether or not there was a vessel detected by the automated algorithm during the same time.

Table 4
Results of generalized linear mixed-effect model selection to determine the best environmental predictors of broadband sound pressure level (SPL; dB re 1 μPa) from 20–100 Hz, 100–1000 Hz, and 1–10 kHz. The best predictive model was determined for each bandwidth by comparing AIC values, with the lowest AIC corresponding to the best explanatory model. Fixed factors included wind speed (kts), wind direction (N/E/S/W), number of AIS vessels within 10 km (AIS), presence/absence of vessel detections ('Detection'), region ('Pair'), and relevant two-way interactions. The random factor included was site (six individual recorder locations). Change in AIC indicated is compared to the full model.

Bandwidth	Factor removed from full model	ΔAIC
20–100 Hz	Detection	687.5
	Wind direction	606.3
	Pair	172.7
	Interactions	149.8
	Wind speed	25.0
	AIS	12.5
100–1000 Hz	Detection	5416.0
	Wind direction	1209.7
	Wind speed	794.1
	Interactions	497.0
	Pair	445.2
	AIS	84.1
1–10 kHz	Detection	10,284.9
	Interactions	5748.8
	Wind speed	2104.8
	Wind direction	1492.7
	AIS	230.4
	Pair	209.7

Victoria (1.22 ± 0.31 dB re 1 μPa, $t_{21640} = 3.95$, $p < 0.001$) and less in Sidney (−0.681 ± 0.271 dB re 1 μPa, $t_{21640} = -2.51$, $p = 0.012$) than in Esquimalt. Although there were significant effects detected for wind speed, wind direction, and the interaction of the two (Table 5), no pairwise comparisons showed significant differences. The significant interaction between wind direction and region might explain why these were such important factors in the explanatory model for this bandwidth (Table 4): wind from the west caused a disproportionate difference in SPL among regions.

The presence of vessel detections had an even greater significant positive relationship with SPL in the 100–1000 Hz bandwidth, with an effect size of 9.3 ± 0.12 dB re 1 μPa ($t_{21640} = 78.48$, $p < 0.001$). The AIS vessel count at a 10 km radius also had a significant effect ($t_{21640} = 9.22$, $p < 0.001$), but again a lower effect size (0.22 ± 0.02 dB re 1 μPa) may account for the lower importance of this factor in model selection (Table 4). Wind speed had a significant positive relationship with SPL (0.14 ± 0.02 dB re 1 μPa/km/h, $t_{21640} = 6.08$, $p < 0.001$), as did the interaction of wind speed and wind direction: easterly wind speed had a significantly greater positive relationship with SPL than the south or the west (−0.073 ± 0.02 dB re 1 μPa/km/h, $t_{21640} = -3.13$, $p = 0.002$). Wind speed and direction likewise both had a significant interaction with region: wind speed had a significantly greater effect on SPL in both Sidney (0.16 ± 0.02 dB re 1 μPa/km/h, $t_{21640} = 8.6$, $p < 0.001$) and Victoria (0.07 ± 0.02 dB re 1 μPa/km/h, $t_{21640} = 4.16$, $p < 0.001$) than in Esquimalt, and all wind directions interacted with region in Sidney (effect sizes between −1.87 ± 0.39 and −5.97 ± 0.39 dB re 1 μPa, all $p < 0.001$), but not in the other regions. Overall, easterly winds had disproportionate impacts on SPL depending upon both speed and region. These interactions may contribute to the relative importance of wind speed and direction in model selection at this bandwidth over region, which was the only factor that showed no significant effect on SPL (Tables 4, 5).

At the 1–10 kHz bandwidth, the presence of vessel detections had a significant positive relationship with SPL, with an estimated effect size of 12.0 ± 0.10 dB re 1 μPa ($t_{21640} = 114.78$, $p < 0.001$). The number of AIS vessels within a 10 km radius also had a significant positive effect on SPL, but the effect size was once again much smaller (0.33 ± 0.02 dB re 1 μPa, $t_{21640} = 15.29$, $p < 0.001$). Wind speed had a greater positive relationship with SPL when it came from the north (0.06 ± 0.02 dB re 1 μPa/km/h, $t_{21640} = 2.9$, $p = 0.004$) than the east; conversely, increased wind speed from the south (−0.08 ± 0.02 dB re 1 μPa/km/h, $t_{21640} = -3.6$, $p < 0.001$) or west (−0.11 ± 0.02 dB re 1 μPa/km/h, $t_{21640} = -5.4$, $p < 0.001$) had significantly less impact on SPL than wind from the east. Similarly to the middle bandwidth, wind direction interacted with region significantly from all directions in Sidney (effect sizes between −1.88 ± 0.38 and −3.81 ± 0.34 dB re 1 μPa, all $p < 0.001$) and from the west in Victoria (0.88 ± 0.39 dB re 1 μPa, $t_{21640} = -2.3$, $p = 0.023$). Wind speed in Esquimalt had a significantly more positive relationship with SPL than at either of the other two regions (effect sizes −0.042 ± 0.02 and −0.10 ± 0.01 dB re 1 μPa, both $p < 0.05$). The significance of these complex relationships to predicting SPL might account for the importance of the two-way interaction terms in model selection at this bandwidth (Table 4). Wind speed had a significant effect on its own, although the effect size was small (0.37 ± 0.02 dB re 1 μPa/km/h, $t_{21640} = 17.8$, $p < 0.001$). Wind direction showed a significant effect overall

Table 5
Analysis of variance table showing results of linear mixed-effects models of sound pressure level (SPL; dB re 1 μPa) at three focal bandwidths. The results of full models including two-way interactions are shown. Degrees of freedom (df) are given in the form 'group, residual'. Sum of Squares (SSquares) are rounded to the nearest whole number. F-values are rounded to the nearest 0.1 unless <1; p-values under 0.05 (*) denote significant effects. Factors are detection (binary), AIS (# of vessels within 10 km range), wind speed (kts), wind direction (N/E/S/W), region ('Pair'), and all two-way interactions among the latter three factors.

Bandwidth	Factor	df	SSquares	F	p
20–100 Hz	Detection	1, 21639	17,628	703.8	<0.001*
	AIS	1, 21639	393	15.7	<0.001*
	Wind speed	1, 21639	689	27.5	<0.001*
	Wind direction	3, 21639	1236	16.4	<0.001*
	Pair	2, 3	28	0.56	0.621
	Wind speed * Direction	3, 21639	468	6.2	<0.001*
	Wind speed * Pair	2, 21639	606	12.1	<0.001*
	Wind direction * Pair	6, 21639	3353	22.3	<0.001*
100–1000 Hz	Detection	1, 21639	314,325	6159.4	<0.001*
	AIS	1, 21639	4342	85.1	<0.001*
	Wind speed	1, 21639	33,540	657.2	<0.001*
	Wind direction	3, 21639	3648	23.8	<0.001*
	Pair	2, 3	260	2.5	0.225
	Wind speed * Direction	3, 21639	1771	11.6	<0.001*
	Wind speed * Pair	2, 21639	3790	37.1	<0.001*
	Wind direction * Pair	6, 21639	21,308	69.6	<0.001*
1–10 kHz	Detection	1, 21639	527,431	13,174	<0.001*
	AIS	1, 21639	9356	234	<0.001*
	Wind speed	1, 21639	75,779	1893	<0.001*
	Wind direction	3, 21639	2254	19	<0.001*
	Pair	2, 3	6	0.01	0.931
	Wind speed * Direction	3, 21639	5348	45	<0.001*
	Wind speed * Pair	2, 21639	2159	27	<0.001*
	Wind direction * Pair	6, 21639	6711	28	<0.001*

(Table 5); however, none of the pairwise comparisons showed significant differences.

3.5. Factors influencing disturbance

A binomial generalized linear model was used to examine which of the explanatory variables above had an influence on whether the SPL in the critical bandwidth for rockfish communication (20 Hz–1 kHz, or the summed SPL of the two lower bandwidths examined above) exceeded our masking threshold of 113 dB re 1 μPa. Threshold exceedance was more likely when vessels were detected (effect size = 1.63 ± 0.04, $z_{1,43,305} = 45.29$, $p < 0.001$), and with increasing numbers of AIS vessels (effect size = 0.04 ± 0.01, $z_{1,43,305} = 6.06$, $p < 0.001$). Region had a significant impact, with Esquimalt sites being more likely to exceed the threshold than Victoria (effect size = −1.99 ± 0.18, $z_{2,43,305} = -11.24$, $p < 0.001$) or Sidney sites (effect size = −0.47 ± 0.11, $z_{2,43,305} = -4.41$, $p < 0.001$). However, this effect was moderated by an interactive effect of region and wind direction, with winds from the south and west having less impact on threshold exceedance in Victoria than those from the east and north in Esquimalt. Winds from the east had greater impact on threshold exceedance in Sidney than those from any other direction when compared to Esquimalt. The presence of vessel detections had the greatest overall impact on the likelihood of SPL exceeding the threshold at which communication masking may take place in rockfish.

4. Discussion

We have not found evidence that Rockfish Conservation Areas (RCAs) in the Salish Sea provide consistent protection against potentially disruptive levels of anthropogenic noise compared to nearby unprotected areas. The RCA sites had approximately equal (20–100 Hz bandwidth) or lower noise levels (100 Hz–10 kHz bandwidths) compared to unprotected reference sites; however, this trend was inconsistent in both time and region. Here we present evidence that anthropogenic noise, both inside and near RCAs, is elevating sound pressure levels (SPL; dB re 1 μPa) within the critical frequency band for rockfish above a theoretical threshold at which behavioural disturbance to rockfish could occur *via* communication masking (Clark et al., 2009). All recording locations, regardless of protection status, contained recordings that exceeded this limit during all recording periods. Despite RCA locations having fewer exceedances than unprotected sites, our findings nevertheless represent a potential for disturbance at all sites, especially in busier seasons. Discovery Island RCA exceeded the disturbance threshold in over 10% of recordings overall, and Fernie Island (inside the Coal Island RCA) in approximately 5% of recordings overall. This concern is compounded by the fact that two unprotected sites nearby to RCAs (Macaulay Point and Armstrong Point) had over 23% of all recordings exceeding the masking threshold, and over 30% of recordings in the spring. These sites, while not in protected habitat, would be considered good quality rockfish habitat for management purposes (Fisheries and Oceans Canada, 2008). The high incidence of noise exceeding our disturbance threshold at these sites suggests that there may be edge effects around RCAs in terms of vessel traffic, which have the potential to impact rockfish recovery efforts (Pirotta et al., 2019).

As hypothesized, the presence of vessels (using either AIS records or the vessel noise detector) accounted for a significant amount of variation in SPL at each focal bandwidth, as well as making it significantly more likely that the SPL in the critical bandwidth for rockfish vocalizations would exceed the theoretical masking threshold of 113 dB re 1 μPa. There were more vessels detected in fall and spring than in winter overall, which corresponds to a rise in recreational vessel and tourism activity in the summer seen in the Salish Sea (*e.g.* Houghton et al., 2015) and elsewhere (*e.g.* Rako et al., 2013; Hermannsen et al., 2019). The Sidney pair had the most AIS-carrying vessels as well as total vessel detections consistently throughout the year, likely due to their proximity to two ferry terminals, one of which runs all year and the other from spring to fall, as well as several marinas and popular fishing and diving destinations visited by recreational as well as commercial (AIS-enabled) vessels. The Esquimalt pair had fewer vessels detected than the Victoria pair, but a higher proportion of AIS-enabled vessels throughout the year. This is likely due to Esquimalt's proximity to Victoria harbour to the east (two year-round ferry routes, a cruise ship port, commercial tourism and fishing vessels, tugs, and a pilot station), Canadian Forces base Esquimalt to the west (naval vessels), and international shipping lanes <10 km to the south. Victoria, on the other hand, is closer to a recreational boat launch, popular recreational fishing, diving, and tourism destinations which likely increases the amount of vessel traffic overall in this area; however, these sites are only regularly exposed to large AIS-enabled vessels *via* the shipping lane in Haro Strait to the east.

We expected that the vessel detector would more closely predict SPL and disturbance threshold exceedance than would the AIS vessel counts for two reasons: first, not all boats in this area carry AIS transponders (*e.g.* recreational boats), therefore the acoustic vessel detector would ideally detect noise from every vessel; second, because our deployment sites were in shallow water areas (<20 m depth), and therefore frequencies up to ~50 Hz (depending on bottom composition and slope) would propagate poorly because the wavelength of these signals is greater than the depth of the water column (Richardson et al., 2013; Hermannsen et al., 2019). This second hypothesis is most relevant for more distant vessels with higher source levels, where only low frequency (<100 Hz) signals would be expected to propagate over the distance to the acoustic recorder. Due to the shallow water depth, our acoustic recorders may not have picked up signals from these vessels.

The first hypothesis was supported by differences between vessel detector results and AIS vessel counts at any range, as well as the vessel detector being a more important predictor of SPL than AIS vessel counts in the explanatory models. AIS counts had much lower effect sizes compared to vessel detections. However, AIS vessel counts were not redundant to vessel detections, and were found to be significant factors explaining SPL at all of our focal bandwidths as well as a significant factor in whether a recording exceeded the disturbance threshold. Commercial vessels equipped with AIS usually have high source levels (Erbe et al., 2012), but the vessel detector cannot differentiate between these and smaller vessels with lower source levels. It is possible that including the AIS variable may actually correct for the vessel detector, accounting for additional SPL not accounted for by the vessel detector. Although the current study and others show that recreational vessels have a larger impact on noise levels near shore (*e.g.* Hermannsen et al., 2019), this correction factor would support the continued inclusion of AIS data for noise budgeting, provided that recreational traffic is also considered.

The second hypothesis above was supported by relatively low and consistent SPL in our lowest bandwidth (20–100 Hz), likely due to the fact that none of our sites were close enough to recreational thoroughfares, shipping lanes, or ferry routes for low-frequency noise from either AIS-enabled or non-AIS vessels to propagate upslope to our shallower recording sites (Richardson et al., 2013). This also agrees with our findings that the effect sizes of both AIS vessel counts and vessel detections on SPL increased with increasing frequency, though vessel detections were far more important at all bandwidths. This result suggests that nearby recreational motor vessels had a greater effect on the soundscape at all bandwidths than did larger AIS-enabled ships, which is consistent with similar findings in the same area (Veirs et al., 2016; Archer et al., 2018; Cominelli et al., 2018), as well as in shallow coastal waters elsewhere (*e.g.* Hermannsen et al., 2019). Because this bandwidth is within the critical bandwidth for rockfish vocalizations (20 Hz–1 kHz), future studies of anthropogenic noise in RCAs should consider deeper recording sites in nearby RCAs with a greater depth profile. Deeper-water recordings would be helpful to determine whether noise from larger, farther-away boats can be heard at greater depths, but would also require different deployment strategies for acoustic recorders due to the depth limitations of divers, which was an important consideration for our site selection in this study.

Environmental conditions and their interactions with location also significantly impacted SPL at all bandwidths as well as disturbance threshold exceedance. The spatial factor of region (three pairs of sites) was not a significant predictor of SPL at any bandwidth, but had interactive effects with both wind direction and wind speed at all bandwidths. This interaction suggests that spatial autocorrelative effects were mediated primarily by differences in wind exposure and prevailing wind direction among regions. For instance, westerly winds were more important at Victoria, which is exposed to wind coming down Juan de Fuca Strait from the ocean, than in Sidney, which is sheltered from westerly winds by Vancouver Island (Fig. 1). Wind speed had a significant impact on SPL at all bandwidths, which is consistent with predictions made according to the Wenz curve for higher-frequency wind noise and with low-frequency wind noise in shallow water (Richardson et al., 2013); however, interpretation of this effect is hindered by interactions with direction and region. In addition, interactive effects with region that were not investigated, but may have impacted SPL levels, include bottom topography, water currents and tidal motion, macroalgal cover, and anthropogenic noise sources unrelated to vessels (*e.g.* the presence of underwater power lines or industrial sites close by) (Wenz, 1962; Richardson et al., 2013; Haxel et al., 2013). Region did have a significant impact on the likelihood that a recording would exceed the disturbance threshold for rockfish, but once again, this effect was dependent upon wind direction, with some wind directions having a greater impact than others.

In addition to our acoustic findings, our rockfish counts support recent literature showing little difference in rockfish population size between RCAs and unprotected habitat of similar quality (Haggarty et al., 2016b). Rockfish numbers were consistently high at only one of three RCA sites (Discovery Island), and similarly high at one of the unprotected sites (Armstrong Point). From our SCUBA surveys, there was little effect of protection status on the number of rockfish seen while deploying and retrieving equipment throughout the study. There was also no visible trend linking the number of rockfish seen at any site during a certain season with noise level at any bandwidth. For instance, we found more rockfish throughout the year at Armstrong Point, which was unprotected, than at its paired location of Fernie Island (Coal Island RCA), despite both sites having high amounts of boat noise. Conversely, Macaulay Point, which had nearly 7% of recordings exceed the marine mammal disturbance threshold, and its paired site Duntze Head RCA (less than 0.2% of recordings over the threshold), both had low numbers of rockfish observed throughout most of the year, with the exception of a school of rockfish seen at the RCA site in June. While our surveys were rapid and opportunistic, this lack of trend nevertheless suggests that the presence of rockfish at these sites is not strongly driven by noise level or by protection status. Similar study designs have been conducted using SCUBA transects in RCAs and unprotected habitat at similar depths in the same geographical area (Cloutier, 2011; Borden et al., 2018), and one found a positive effect of RCAs on density, though not presence/absence, of several species of rockfish (Cloutier, 2011). Haggarty et al. (2016b) surveyed sites nearby to ours with a remotely-operated vehicle, which enabled greater depth range (25–125 m), and found no difference in size or density of fish inside RCAs compared to reference sites; habitat quality variables accounted for more variability in fish quantity both inside and outside of RCAs.

In the present study, increases in ambient noise were related to the presence of vessels, and occurred not only within RCAs, but to a greater extent in habitat adjacent to RCAs, where fishing is still allowed and where, presumably, managers are hoping to see an increase in rockfish density as populations recover (Kritzer, 2004; Yamanaka and Logan, 2010; Haggarty et al., 2016b). There is increasing evidence that simply setting aside areas for at-risk species does little to protect those areas from anthropogenic noise (Buscaino et al., 2016). In the terrestrial environment, Buxton et al. (2017) found that anthropogenic noise caused a ten-fold increase in background noise levels in 21% of the United States' wildlife preserves, including critical habitat for endangered species. In offshore marine environments, Allen et al. (2018) correlated shipping traffic up to 50 km away with ambient noise increases at a deep-water offshore Marine Protected Area in British Columbia. Shipping and ferry lanes like the ones transiting the Salish Sea (Fig. 1) increase the SPL in critical bandwidths for several at-risk marine mammals over wide areas (Erbe et al., 2012; Pirotta et al., 2019). It has been suggested that vessel thoroughfares be treated as marine 'roads' for ecological and spatial planning purposes, with the recommendation of adding 'transition zones' between critical habitat and shipping lanes (Pirotta et al., 2019). This was not a consideration when planning and implementing RCAs in British Columbia over a decade ago (Fisheries and Oceans Canada, 2008; Yamanaka and Logan, 2010), resulting in many RCAs positioned directly adjacent to shipping lanes and ferry routes with no buffer zone between them.

The primary goal of RCAs is to increase rockfish stocks inside and outside RCAs by providing refuge from fishing pressure (Yamanaka and Logan, 2010). However, since their inception, RCAs have come under criticism for not taking into account several habitat variables (Cloutier, 2011; Tonnes, 2011; Haggarty and Yamanaka, 2018), extent of home range and historical range of several species (Love et al., 1990; Hannah and Rankin, 2011; Rodrigues et al., 2018), and ecosystem impacts such as increasing predation pressure within RCAs (Beaudreau and Essington, 2007; Cloutier, 2011; Ward et al., 2012). A lack of education and enforcement early in their implementation also led to poaching inside RCAs in our study area (Lancaster et al., 2015, 2017; Haggarty et al., 2016a). Given our results, RCA placement in the Salish Sea also failed to consider noise pollution. Further, if RCAs are intended to be places for rockfish to breed, and if rockfish use vocalizations to facilitate breeding (Širović and Demer, 2009), then noise pollution might hinder mate selection or cause rockfish to breed outside of protected zones. It is currently unclear whether rockfish use vocalizations to facilitate breeding through chorusing like many other demersal and reef-dwelling fishes (McKibben and Bass, 1998; Ghazali, 2011; Rowell et al., 2017). To confirm this link between population health and communication masking by noise pollution, we recommend further study of rockfish vocalizations and breeding behaviour using promising new technology that allows concurrent visual and acoustic observations (*e.g.* Mouy et al., 2019). The passive acoustic data collected as part of this current study will be valuable for future studies on vocalizations by rockfish and other fish species, and a useful follow-up could be to examine potential communication masking during times when rockfish vocalizations are detected to better examine the spatial and temporal extent of communication masking in this region.

Here we have presented evidence corroborating previous studies to conclude that lines on a chart representing the boundaries of RCAs are not an effective barrier to anthropogenic noise. While research on the direct impacts of anthropogenic noise on rockfish species is lacking, there is mounting evidence that anthropogenic noise has indirect impacts on the habitat quality and life history of other fish species, as well as other taxa that make up the complex ecosystem that rockfish inhabit (Erbe et al., 2016; Carroll et al., 2017; Murchy et al., 2019). Furthermore, we present evidence that rockfish vocalizations may be subjected to communication masking (Clark et al., 2009; Stanley et al., 2017) within critical habitat, both protected and unprotected. Based on our findings, we suggest that future RCA development as part of an adaptive management plan consider sources of noise pollution in the planning stages, and that further research should prioritize experimental studies of the behavioural and physiological impacts of noise on rockfish. Further work investigating the biological consequences to rockfish of the noise pollution present in and around RCAs will help to inform managers whether further efforts are required to increase stocks of these commercially and ecologically important at-risk fish species.

CRediT authorship contribution statement

Katrina Nikolich: Conceptualization, Methodology, Investigation, Formal analysis, Writing – original draft. **William D. Halliday:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. **Matthew K. Pine:** Methodology, Software, Validation, Formal analysis, Writing – review & editing. **Kieran Cox:** Investigation, Visualization, Supervision, Writing – review & editing. **Morgan Black:** Investigation, Methodology, Supervision, Writing – review & editing. **Corey Morris:** Funding acquisition, Resources. **Francis Juanes:** Conceptualization, Resources, Project administration, Funding acquisition, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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